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Life cycle impacts of soil construction, an innovative approach to reclaim brownfields and produce nonedible biomass

Jérémy Rodrigues [a, 1], Antoine Gérard [b], Geoffroy Séré [c], Jean-Louis Morel [c], Sophie Guimont [d], Marie-Odile Simonnot [a], Marie-Noëlle Pons [a, *]

[a] Université de Lorraine, CNRS, LRGP, F-54000, Nancy, France
[b] Progépi, 1 rue Grandville, 54000, Nancy, France
[c] Université de Lorraine, INRA, LSE, F-54000, Nancy, France
[d] Valterra Dépollution Réhabilitation, 3 Allée de Chantilly, 54500, Vandœuvre-lès-Nancy, France

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ABSTRACT

The objective of the LORVER project was the construction of fertile Technosols on an industrial brownfield using wastes and byproducts to produce biomass for industrial purposes (hemp as a fiber source and poplar for short rotation coppice). A Life Cycle Assessment (LCA) of the Technosol construction was conducted to highlight the most significant environmental contributions. Three scenarios were compared: a reference scenario (REF) without improvement of the brownfield, a Technosol scenario (LORVER) using industrial byproducts (treated excavated soil, dredging sediments, paper mill sludge, compost and green waste) and a scenario where the brownfield was covered by topsoil (TS). An LCA was performed using SimaPro 8.5, the Ecoinvent v3 database and the ILCD impact indicators.

The main contributors to the LORVER scenario that affected air quality and had energy-related impacts were the indirect demand of quicklime due to the use of paper mill sludge, which would have otherwise been spread on fields to save calcic amendments, followed by the transportation of waste from its source to the brownfield site. For the REF and TS scenarios, transportation and organic material spreading caused the most significant impacts. The LORVER scenario was the best or one of the best options for the fertility, carbon and pollution regulation-related impact categories due to the high carbon storage capacity of Technosols and its potential as an alternative solution to waste landfilling.

Sensitivity analyses have shown that the LORVER scenario was always the best scenario for the climate change and land-related impacts and that it outperformed alternative scenarios if their required transportation distances exceeded 200 km. This very first LCA of a constructed Technosol made of inert and organic wastes on a brownfield site has proven the merit of this new approach, provided that environmental impacts are evaluated on a case-by-case basis, with the main variability source being the used materials and their alternative management strategies. It has also been demonstrated that these unused soils and materials could provide provisioning, regulation and cultural ecosystem services.

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1. Introduction

Since the 19th century, the consumption of energy and mineral resources has increased steadily, because of an increase in the world population and the average living standards, especially in emerging countries (Hudson, 1992). The latter show the largest individual consumption of resources—and the associated greenhouse gas emissions—(Fischer-Kowalski et al., 2011; Chancel and Piketty, 2015).

The result of these trends is an increase in the human predation of natural resources, which are available in limited quantities (Fischer-Kowalski et al., 2011). In addition, the quality of the available deposits is constantly declining for both energy and mineral resources (Hirsch et al., 2005; Boryczko et al., 2014), resulting in a higher energy consumption per unit of energy/extracted resource (Mudd, 2010).

Under these conditions, mankind must significantly reduce its dependence on nonrenewable resources and engage in eco-friendly

* Corresponding author.
E-mail address: Marie-Noelle.Pons@univ-lorraine.fr (M.-N. Pons).
[1] Present address: BRGM, 45100, Orléans, France.

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production and consumption patterns, *i.e.,* which minimize the negative impacts on the nonrenewable resources or even help to restore them. Among the options available for this purpose, the production of biomass to produce energy, materials or molecules of interest presents interesting prospects but faces possible conflicts of use with the production of food (Jezierska-Thöle et al., 2016; Cobuloglu and Büyüktahtakin, 2017) and the preservation of biodiversity, already under pressure (Fernando et al., 2015). Indeed, edible crops such as wheat, maize, sugar beet, sugar cane (Bos et al., 2012), and sweet potatoes (Koçar and Civaş, 2013) can be used to produce bioethanol as an energy vector as well as a bulk resource for chemicals (PVC, polyethylene, PLA, etc.). The first LCA studies on these biomass crops were focused on greenhouse gas emission limitation and the reduction of fossil resource depletion. More recently, the question of land use and of land use change (either direct or indirect) has become more prevalent (De Baan et al., 2013; Tang et al., 2018; Li et al., 2018). There are still many discussions on how to address their modeling (Whitaker et al., 2018; Saez de Bikuña et al., 2018; De Rosa, 2018). The type of descriptors to consider is also not yet well defined (Perminova et al., 2016; Taelman et al., 2016). If some descriptors (*e.g.,* the soil organic carbon content (SOC) or the emitted GHG) are potentially relatively easy to evaluate, the biodiversity is more complex to quantify (Dauber and Miyake, 2016; Chaudhary and Brooks, 2018).

A more socially acceptable path, envisioned for several years, is to produce all or part of this biomass on degraded or marginal land, *i.e.,* considered unsuitable for food production because it is not fertile enough, polluted or degraded by past human activities (Liu et al., 2017; Laasasenaho et al., 2017; Fernando et al., 2018). Such areas, which are very common in regions with a strong industrial past, require a reclamation process to neutralize the risks associated with their pollution and to provide essential functions for nearby activities (*e.g.*, regulation of water flows, biodiversity). However, deindustrialization often comes with a lack of economic dynamism that leads to a spreading of brownfields. Biomass production in these areas can be a long-term, relatively inexpensive and cost-effective method of rehabilitation through the economic valuation of crops. However, the degraded nature of soils can hinder the establishment of a crop, so adaptations of the environment may be necessary.

Two main options are currently considered: i) an onsite crop without significant soil reclamation, which may lead to poor fertility and then low yields; and ii) an earthwork based on the reconstitution of fertile soil by using topsoil material from surrounding arable areas, which involves heavy transportation and the depletion of a crucial resource: to cover a surface of 1 ha with fertile soil with a layer thickness of 30 cm, 3000 m^3 of material should be transported. However, an emerging ecological engineering approach was recently developed: soil construction (Séré et al., 2008, 2010). Constructed Technosols result from the use of wastes and byproducts to design a fertile soil that is aimed at promoting soil structure, organic matter stabilization and microbial growth (Moreno-Barriga et al., 2017) and can host a large biodiversity (earthworms (Pey et al., 2013), and ants (Vergnes et al., 2017)). Indeed, such artificial soil is at least capable of, if not fully able to reproduce natural soil complexity, to provide analogous levels of ecosystem services (Deeb et al., 2017).

The LORVER project was established in Homécourt (North-East France) on land degraded by long-term coking plant activities to build expertise on soil construction and prove the feasibility of this technique for two crops with contrasting agronomic needs and economic uses. The crops were hemp, cultivated to produce fiber, insulation or composite materials, and poplar in short rotation coppice (SRC) for bioenergy.

If these experiments prove successful, they will constitute an interesting way to simultaneously, rehabilitate degraded lands, recycle wastes in a cost-effective manner, and increase (nonfood) biomass without compromising food crops and biodiversity.

However, the project's environmental impact needs to be assessed to ensure the relevance of such a technique. In this paper, an LCA was conducted to compare the potential impacts of the experimental LORVER supply chains with alternative ways of producing biomass on a brownfield. First, the functions expected from the LORVER and two possible alternative scenarios used for comparison are defined. Second, the models and data used for each life cycle phase are described. The relative environmental impacts are assessed before using sensitivity analyses to change some key parameters of the models. This will allow to identify its strengths and weaknesses, as well as the conditions in which the LORVER scenario has the most beneficial supply chain.

2. Goal and scope of the study

2.1. Functional units and studied scenarios

The goal is to assess the potential impacts of several supply chains able to simultaneously: reclaim 1 ha of degraded land and allow protection of the groundwater table from contamination, produce biomass equivalent, in both quantity and quality, to 20 years of profitable production on 1 ha, and give value to byproducts or wastes, among those described in Table 1 by soil construction.

The 20-year limit was considered long enough to ensure yield stabilization after the conversion of the brownfield to agricultural purposes. However, a higher limit would require taking the impact of climate change on yields into account.

This study aims to highlight the most significant contributors to the life cycle impacts of these supply chains in a given context, as well as the conditions in which each one of them causes the lowest environmental impact. Three scenarios are considered with regards to how they satisfy these functional units (brownfield reclamation, biomass production, waste elimination or valorization):

1) REF: a reference scenario in which biomass is produced directly on the brownfield soil, without any soil material inputs. Due to the degraded nature of the soil, yields are expected to be much

Table 1
Description of byproducts to eliminate or recycle.

Byproduct or soil	Origin and description	Current elimination chain
Treated excavated soils	Various soils with poor agronomic potential originating from industrial sites, have undergone biological treatments to degrade their organic pollutants	Inert landfill
Dredging sediments	From the nearby Moselle River	Inert landfill
Paper mill sludge	From industries relatively close to the experimental site Potentially high agronomic value	Agricultural spreading (avoids lime)
Compost and green waste	High organic matter and nutrient content	Agricultural spreading (avoids fertilizers)

lower than on a "healthy" soil. The resulting shortfall is produced elsewhere, increasing the pressure on agricultural and natural land. Byproducts follow their current elimination chain;
2) LORVER: byproducts or inert wastes generated by nearby industries are recycled into a constructed soil, implemented on the brownfield to ensure a biomass production equivalent to that of a "healthy" soil. All the materials are under the limits concerning mineral and organic pollution, and their use is legally authorized.
3) TS: arable topsoil originating from a current building site is transported to the brownfield to achieve satisfying yields. If not imported to the brownfield, this topsoil would supposedly have remained near its site of origin to be used by other development projects. Byproducts follow their current elimination chain.

To put these scenarios in context, REF would occur if only little funding was available for a heavy and quick rehabilitation of the brownfield. Biomass production would only be a side-benefit at the brownfield scale. To satisfy local needs, additional land would be required. The TS scenario would occur, instead, if more funding allowed the massive import of higher quality soil, to ensure quick and decent yields at the brownfield scale.

It was chosen to conduct an attributional LCA – *i.e.,* based on average technology applications and allocation strategies. In the future, a consequential LCA could account for the impact of the studied chains on local markets, but data were insufficient to perform it for now.

2.2. Studied crops

Hemp and poplar have contrasting agronomic needs, so the constructed soil they require should have different properties and compositions for the plants to grow properly. Hemp needs good water drainage of the soil, ensured by a high proportion of coarse soil material. SRC requires a clayey soil that is capable of storing high amounts of water (Guittonny-Larchevêque and Lortie, 2017). These differences have an impact on the quantities and types of byproducts to be used or managed otherwise in alternative scenarios. They therefore help to highlight the influence of certain phases on the life cycle impacts of the supply chains.

Table 2
Phases included in the life cycle of studied scenarios (contrib. = Phase contributing to impacts of studied scenario).

	REF	LORVER	TS
Process generating *byproduct or topsoil*	*Phase out of the scope*		
Byproduct end of life			
Transportation			
To brownfield		contrib.	
To alternative byproduct elimination site	contrib.		contrib.
End of life processes			
Soil construction (on brownfield)		contrib.	
Byproduct elimination	contrib.		contrib.
Indirect demand for inputs[a]		contrib.	
Topsoil use			
Transportation			
To brownfield			contrib.
To alternative topsoil use site	*Phase out of the scope*		
Use processes			
Soil construction (on brownfield)			contrib.
Alternative use	*Phase out of the scope*		
Biomass production			
On brownfield	contrib.	contrib.	contrib.
On additional land (for shortfall)	contrib.		
Biomass transformation	*Phase out of the scope*		

[a] If a byproduct is used in a constructed soil, it is no longer available for other recycling chains, and thus, indirectly increases demand for other products.

2.3. Included processes

Table 2 describes the different phases involved in the different supply chains. They include i) biomass production on the brownfield (all scenarios) and on potential additional land, if needed (REF), and ii) topsoil transportation from the original building site to the brownfield (TS). For the considered byproducts, transportation is included, either to the brownfield where they would be incorporated into a constructed soil (LORVER) or to their alternative disposal chain (REF, TS), as well as the considered processes of recycling/disposal. Finally, in the case of the LORVER scenario, the indirect input demand increase is implied by the avoidance of the recycling of byproducts. Indeed, if not used to construct a soil, some byproducts would be recycled to reduce the demand for inputs (*e.g.,* fertilizers, lime). Then, the soil construction, by "avoiding" such recycling, may indirectly imply an increased input consumption, which is included in the scope of this study.

The inclusion of the latter is motivated by the need to make a fair comparison. Because the studied systems are multifunctional, they were expanded according to the ILCD recommendations. In doing so, an additive approach is first used (Fig. 1) to avoid negative impacts – or so-called impact savings. Later, when comparing different cropping systems, the subtractive approach will be used because this approach better handles changes in the quantities of byproducts to eliminate/incorporate in a constructed soil.

Conversely, the processes generating byproducts and the topsoil excavation are not included in the scope because they would supposedly occurred anyway: they originate from industrial or construction activities that are independent from the studied brownfield rehabilitation. They differ, however, in the way their "alternative end of life" is handled. On the one hand, byproducts are assumed to be of little – if not negative – economic value because their producers may have to pay for their disposal. Branded as waste, their elimination is a function that needs satisfaction. On the other hand, topsoil is assumed to always find trade opportunities such as green areas in cities near the building sites they were extracted from. Therefore, in this paper, excavated topsoil is considered as a product and its alternative use as irrelevant, hence its exclusion from the scope of this study.

Finally, biomass transformation is also outside the scope of this study because the origin of the biomass is considered not to significantly impact its properties. Naturally, for biomass growing on a degraded soil (REF), a quality deterioration may be noticed, but then again, this justifies the simulation of much lower expected yields on such a soil and the need for additional land to produce the shortfall. Therefore, for the sake of comparison between different supply chains, its study is not relevant.

In summary, scenarios LORVER and TS differ from REF in that the former could help reach higher yields on the brownfield, thus reducing the pressure on land and the need for additional farming for the same biomass production target. However, they require some byproduct/topsoil transportation and processing. Conversely, LORVER avoids other byproduct transportation and disposal/recycling chains, which in turn implies an increased demand for commodities, as a domino effect. Depending on how much transportation and processes are required in a given context, the environmental impacts with respect to each scenario may differ. The question is then to assess the significance of these features. It is done so in this paper, based on data from the two types of crops cultivated in the LORVER project.

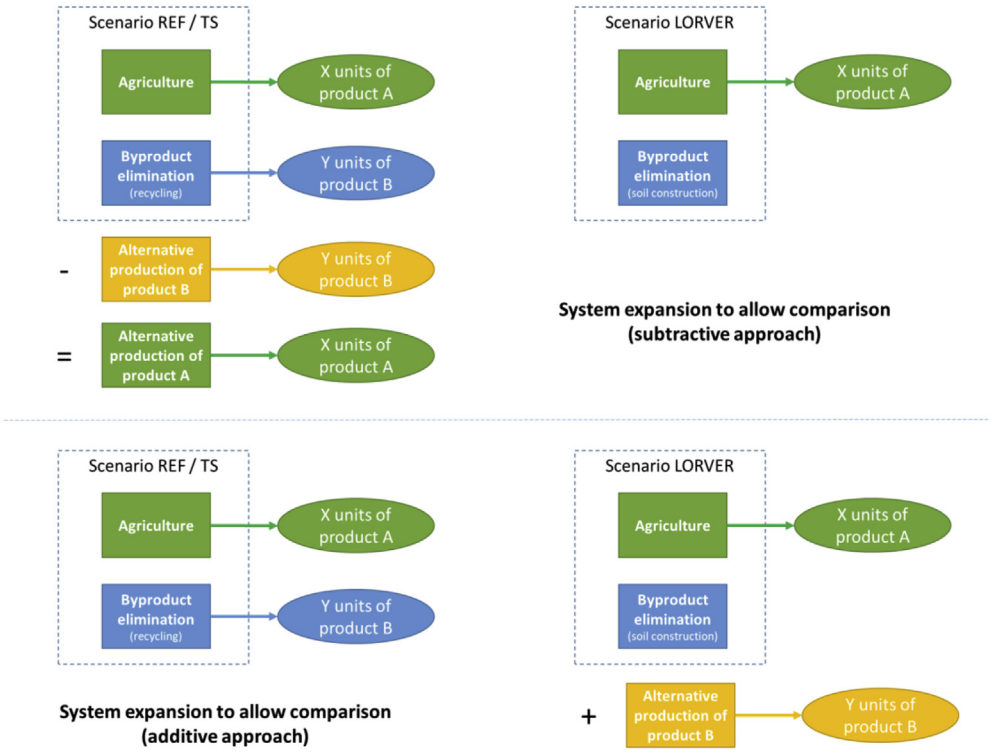

Fig. 1. System expansion to handle multifunctional systems, following two different approaches.

3. Methods and data

After a brief consideration of the databases and impact methods used, this section describes the life cycle phases associated with the studied scenarios.

3.1. Model and impact indicators

The inventory modeling of the different scenarios is performed using SimaPro 8.5 (PRé Consultants, 2015) and the Ecoinvent v3 database. When relevant, the datasets linked to foreground processes have been modified to consider the French electricity mix. This section describes the main data used for the different life cycle phases of the chains.

The selected impact indicators mainly consist of the indicators recommended by the ILCD (EC - JRC - IES, 2011). They comprise the following: i) air quality-related indicators such as climate change, stratospheric ozone depletion, photochemical ozone formation, particulate matter emission and acidifying substances, ii) water quality-related indicators (fresh and marine eutrophication), iii) mineral resource depletion.

Other indicators related to water depletion, toxicity and soil ecosystem services have been studied (Rodrigues, 2016), but their quantification raised many issues, especially due to high flow uncertainty. For the sake of simplicity, they are therefore not discussed here. Instead, the land areas that are modified by the scenarios are simply quantified: natural land clearing, which indicates a potential biodiversity loss, and landscape homogenization and land artificialization, which indicates a profound alteration of basic soil function (water regulation, etc.).

3.2. Material transportation

Table S1 (Supplementary Information) details the quantities and types of materials used for soil construction in scenarios LORVER and TS, as well as their traveled distances from source to brownfield. For instance, 1 ha of soil for hemp culture requires, in the LORVER scenario, 12,620 tons of byproducts that are transported over an average distance of 70 km. In alternative scenarios (TS and REF), they would travel less than 15 km on average to their alternative elimination chain. These weight-averaged distances are calculated using the distances between the byproduct suppliers and the brownfield, located in Homécourt (France), and with alternative disposal/spreading sites. Those latter are, in the context of the case study, exceptionally close.

Topsoil demand in the TS scenario is assumed to be equivalent to that of the total of the byproducts in the LORVER scenario. Indeed, a LORVER-constructed soil is designed to mimic natural soil functions, structure and properties; hence, it probably has the same depth and density as a natural soil.

Topsoil originates from building operations close to the brownfield. The most significant potential suppliers are major urban areas such as Metz and Nancy, resp. 30 and 80 km away from Homécourt. An average distance of 55 km is chosen, suggesting that the topsoil demand generated by the brownfield rehabilitation will certainly be satisfied by several building sites, given the large quantities involved.

When transported to the brownfield, byproducts (and topsoil in scenario TS) are carried by trucks with a 25 t useful load, which is more competitive given the high amounts and distances involved. They use average European technologies. For alternative byproduct uses, transportation is performed over shorter distances and more dispersed around production sites: it is realized with an agricultural trailer.

3.3. Soil construction and alternative end of life

Soil construction, whether using byproducts or topsoil, requires

the following steps:

1) the material is discharged from trucks and piled up on a buffer zone with a skid-steer loader;
2) depending on the soil horizons (or layers) to build, different proportions of materials are mixed together and homogenized with a 25 t hydraulic shovel;
3) the mixtures are then loaded into an agricultural trailer that transports them to the site to rehabilitate, where a skid-steer loader smooths the surface.

The estimated fuel consumption for these operations is 0.57 kg of diesel·m^{-3} of soil. It is roughly the same as the value reported in Ecoinvent processes for quarry rehabilitation operations, which consist of manipulating and moving topsoil layers back where they were before quarrying (Kellenberger et al., 2007).

The alternative use chains vary from one type of byproduct to another: while inert-like materials are usually landfilled, if not useable as construction or earthwork material, organic materials (compost, paper sludge) are usually spread on fields to valorize their agronomic properties. In this paper, based on data collected on the materials used, it is therefore considered that in REF and TS scenarios:

i) inert materials are landfilled to inert waste landfill facilities;
ii) compost is spread on fields, reducing demand for fertilizer inputs: one ton of compost replaces 20 kg of phosphate (P_2O_5), 14 kg nitrogen and 5 kg of potassium (K_2O);
iii) paper sludge is also spread on fields, but its main agronomic interest relies on its high calcium content: one ton of paper sludge replaces 480 kg of quicklime (CaO).

In practice, organic material spreading can either be performed on the brownfield, once biomass production has begun, or on any other field: whatever the case, the fertilizer savings are the same. However, organic matter inputs may have a more beneficial impact on yields on poor soils (*e.g.,* brownfield) than on agricultural soils. Given the lack of data to model this feature, it was chosen to not consider it.

Likewise, in the LORVER scenario, no saving is attributed to organic material use because its role is to restore agronomic properties of otherwise inert and hostile-to-plant growth material.

3.4. Biomass production

This section describes the cropping practices usually implemented for both hemp and poplar in short rotation coppice (Supplementary Information Table S2). These practices are assumed not to vary significantly from one scenario to another. Neither should they vary between the studied brownfield and potential additional land used to reach the required production (scenario REF). This admittedly strong hypothesis is used because of the lack of data for the studied crops on both (1) the effect that strong soil quality differences may have on cropping practices and yields as well as (2) how yields are supposed to evolve over time.

One significant advantage of both hemp and poplar – and the reason why they were chosen in the LORVER project – is that they do not require heavy interventions (pesticide application, frequent monitoring, and irrigation) to grow. The soil was plowed once to control weed, depending on the crop: i) hemp seeds are sown and fertilized to take over quickly, ii) poplar plantlets (20 cm long) are planted into the soil to grow roots and leaves. Only when they can resist weed competition is fertilization applied.

Field emissions (fertilizer run-off or volatilization) are estimated according to the Ecoinvent procedure (Nemecek et al., 2014).

3.5. Sensitivity analysis

Once the most significant contributors to life cycle impacts are identified, a sensitivity analysis is performed to test the importance of key parameters to the LCA. Particular attention is paid to identifying under which conditions the LORVER scenario may – or may not – be the most desirable scenario.

4. Life cycle impact assessment

The life cycle impacts of all the studied scenarios are shown in Supplementary Information Table S3. In this section, the hemp supply chains are analyzed in details. The main contributors to their life cycle impacts based on results displayed in Supplementary Information Fig. S2 are first discussed. Then, the performances of the LORVER scenario are compared to the other scenarios. The SRC supply chains are then compared to the hemp chains to identify which patterns are similar and what their specifications are based on the data in Table S2. Finally, the results of the sensitivity analyses are shown and discussed.

4.1. Main contributors

In the LORVER scenario, the indirectly increased quicklime demand induced by avoiding the need for recycling is the most significant contributor (55–80% of the total) to the air quality and energy-related impacts, as well as the raw material demand, natural land clearing and land artificialization. This is due to the magnitude of the amounts of paper sludge used in soil construction (2400 t·ha^{-1}), the indirect increased quicklime consumption (1152 t·ha^{-1}), and the fact that the fabrication of this input requires extracting and consuming large amounts of fossil energy (more than 100 t of heavy oil).

Byproduct transportation to the brownfield and compost production are the next most significant contributors to those impacts, while brownfield construction work and agriculture are small contributors. The potential release of nutrients and pollutants contained in the byproducts could be the most significant contributor to water eutrophication. Mineral resource depletion is roughly equally distributed between indirect input demand, transportation and agriculture (fertilizers). Finally, land occupation is mostly contributed to by agriculture (70% of the total), while indirect input demand contributes to a fair amount of the rest.

The two other scenarios show roughly similar features between one another because they comprise the same byproduct elimination processes (inert landfill, and organic material spreading), which are large contributors to their life cycle impacts. They mainly differ in their transportation impacts (higher for TS due to topsoil transportation) and agriculture (higher for REF due to lower brownfield yields and increased land needs to produce the same amount of biomass). Hence, TS is always the worst of the two options for impact categories for which agriculture is a minor contributor. It outperforms REF only for land occupation, natural land clearing and water eutrophication.

In both scenarios, organic material spreading is the most significant contributor to climate change, acidification and eutrophication due to the progressive release of nutrients and greenhouse gases during organic matter mineralization. This feature appears most strongly in the LORVER scenario because in that case, organic material is distributed more deeply into the soil, thus reducing its mineralization, which relies on aerobic fauna activity – though long-term experiments are needed to confirm this phenomenon. Inert landfill is the only contributor to land artificialization and raw material demand due to the construction of the landfill. It is also a major contributor to air quality-related impacts, especially ozone

depletion (stratosphere) or formation (troposphere). Finally, agriculture is the most significant contributor to mineral resource depletion, land use and land cover change impacts. This feature is particularly marked within the REF scenario because it accounts for the additional land to be converted and cultivated to produce the biomass needed to cover the same needs as the other scenarios.

4.2. Comparison between scenarios

The LORVER scenario is the best option, or one of the best options, for several impact categories: land artificialization, occupation, natural land clearing, climate change and eutrophication. This is due to its capacity to store carbon and nutrients over longer periods of time and to the fact that it avoids significant inert waste landfill and natural land conversion to agriculture. However, it is the least desirable option in regard to energy or air quality-related impacts. It is indeed hindered by the indirect input demand that it implies, relative to the alternative scenarios that allow byproduct recycling.

Would the production of those inputs be less energy consuming, its performance would be equivalent to, or even better than, alternative scenarios? This is not a merely theoretical exercise: in practice, spreading paper sludge may replace inputs that are much less energy demanding than quicklime, *e.g.,* crushed limestone, depending on the price of the commodities, the farmer's preferences and needs. As it turns out, assuming that paper sludge spreading replaces quicklime spreading is a rather pessimistic hypothesis from the LORVER perspective. This feature will be discussed in the sensitivity analyses.

4.3. Case of the short rotation coppice

Based on the results compiled in Fig. S2 (Supplementary Information), the contributions of each phase to the life cycle impacts of SRC chains can be evaluated. Interestingly, this crop shows very similar patterns to that of hemp. Thus, for the LORVER scenario:

- The indirect use of energy-intensive quicklime is a major contributor to the vast majority of the energy/resource consumption and land clearing/artificialization impacts and to an even stronger extent than for hemp because larger quantities of paper sludge are involved;
- The cropping system is still a minor contributor to those impacts;
- Byproduct nutrients are the main cause of eutrophication impacts;
- Agriculture is a major contributor to land occupation, although indirect quicklime demand becomes a strong competitor.

For the other scenarios, similar to hemp, transportation and agriculture are the main distinguishing features. Organic material spreading remains the most significant contributor to climate change, acidification and eutrophication. However, the relative contribution of inert landfill is less significant – to the "benefit" of byproduct transportation – because inert waste is incorporated in smaller proportions in the constructed soil than it is for hemp culture.

When all scenarios are compared, the indirect quicklime demand penalizes the LORVER scenario to an even larger extent than for the hemp cultures. Thus, it reinforces the disadvantage of the LORVER scenario for resource/energy-related impacts and severely compromises its advantage regarding land occupation and natural land clearing.

It follows that, interestingly, the cropping systems play a small role in the comparison due to their small contribution to the overall impacts. Their main contribution is indirect, depending on the different agronomic needs of the crops, which imply different constructed soil formulations and thus different elimination chains and indirect input demands.

5. Sensitivity analyses

The previous sections emphasized that the indirect input demand is the "trouble-maker", since without it, a LORVER scenario would undeniably by the least damaging scenario. It also highlighted the fact that the nature of the said inputs – quicklime – was a rather pessimistic hypothesis. This raises the question of the necessary reduction in indirect input demand impacts for LORVER to be the best option. This reduction could be due to several factors:

- a cleaner way of producing quicklime, using less (polluting) fossil fuels;
- a smaller substitution effect due to a lower agronomic value, from the mineral amendment perspective. This lower agronomic value could, however, reduce the relevance of the byproduct as an input to soil construction;
- a preference of the farmers needing mineral amendments towards less polluting inputs, such as limestone.

The first sensitivity analysis considers these features altogether, wrapped up into the single perspective of the overall impacts of the indirect input demand, considering exactly how much they need to be reduced for the LORVER scenario to be the most interesting one.

To a lesser, but more pragmatic extent, one notices that transportation needs significantly differ between all supply chains.

This is especially due to the spatial configuration of the case study, where inert waste can be landfilled very close to its generation site. In practice, transportation needs may vary significantly depending on the location of the sources of topsoil and sinks of wastes and byproducts. Therefore, a second sensitivity analysis determines the minimum distance gap for LORVER to be the best case scenario.

5.1. Indirect demand impacts

The minimum factor k by which the indirect input demand impacts should be reduced, for the LORVER scenario to be the best option, depends on the impact in question. It is calculated, for each impact category, with Equation (1) and summarized in Supplementary Table S4:

$$k = 1 - \frac{I_{min} - I_{dir}}{I_{ind}} \quad (1)$$

where I_{min} is the smallest total life cycle impact between REF and TS, I_{dir} the impact associated with the direct life cycle phases of the LORVER option, and I_{ind} the impact associated with the indirect product demand. Indeed, for the LORVER scenario to be the best option requires the following equivalent conditions:

$$I_{LORVER} < I_{min} \Leftrightarrow I_{dir} + (1-k) \cdot I_{ind} < I_{min} \quad (2)$$

Then, three configurations are possible:

- $k \leq 0\%$: LORVER is already the best option for the considered impact, in the studied context, even when including the indirect input demand (climate change, terrestrial eutrophication, land artificialization);

- $k > 100\%$: LORVER cannot be the best scenario under the given conditions because even without the indirect demand, it would be the most detrimental option (energy demand and ozone impacts);
- $0 < k \leq 100\%$: LORVER can be the best scenario provided a reduction of the indirect input demand impacts (all the other impacts).

5.2. Minimal distance gap

Another key parameter is the distance traveled by the waste from the production to the elimination site, as well as by topsoil used in brownfield rehabilitation. It can be perceived as a measure of the value placed on the services of byproduct elimination/recycling and brownfield rehabilitation. Indeed, if stakeholders are ready to transport these materials across long distances to recycle/use them – and incidentally pay high transportation costs – that must mean that these services have some value to them, especially if alternatives exist that require less transportation.

In this study, if not used in a constructed soil, byproducts are eliminated very close to their source (<15 km), contrary to the large distances they have to transported across, when incorporated into a constructed soil (>70 km): in that case, very large amounts of materials are needed and concentrated from varied and rather dispersed origins.

However, in general, the situation may be more favorable to soil construction:

- inert materials may not be landfilled so close to their source, but rather approximately 30 km away;
- organic byproducts may tend to saturate the local spreading capacities and need to travel longer distances;
- topsoil for reclamation can be imported from much further away if the economics of the rehabilitation allows it.

Thus, it is relevant to isolate the transport impacts in the life cycles attributed to each scenario and determine the minimum distance gap required for the LORVER scenario to be the best one:

$$\begin{cases} I_{LORVER}^{TOT} = d_{LORVER} \cdot i_{LORVER}^{transport} + I_{LORVER}^{indirect} + I_{LORVER}^{other} \\ I_{REF}^{TOT} = d_{REF} \cdot i_{REF}^{transport} + I_{REF}^{other} \end{cases} \quad (3)$$

where I_S^{TOT} is the total life cycle impact of scenario s, d_S its average travel distance (km), $i_S^{transport}$ its transportation impact per km, and I_S^{other} its remaining impact. In the case of the LORVER scenario, $I_{LORVER}^{indirect}$ is the impact associated with the indirect input demand increase.

Then, LORVER is the best case scenario under the following conditions:

$$I_{LORVER}^{TOT} < I_{REF}^{TOT} \Leftrightarrow d_{REF} > \left(\frac{I_{LORVER}^{indirect} + I_{LORVER}^{other} - I_{REF}^{other}}{i_{REF}^{transport}} \right) + d_{LORVER} \cdot \frac{i_{LORVER}^{transport}}{i_{REF}^{transport}} \quad (4)$$

It is worth highlighting the correction factor assigned to the travel distance d_{LORVER}, as it expresses the difference in transportation modes. Indeed, because a LORVER scenario requires transportation of massive amounts of materials to one single destination – the brownfield to rehabilitate – it allows the use of cleaner and more efficient equipment per ton transported. Thus, the impact reduction per km scales up to between 12 and 64%, with an average of 38% (Supplementary Table S5).

The results of these sensitivity analyses are summarized in the Supplementary Information section (Tables S4 and S5, Figs. S3 and S4). They highlight that:

- the LORVER scenario is always the best case scenario for climate change and land-related impacts – assuming that it stabilizes organic matter over longer periods of time than agricultural spreading and that it helps reach higher yields than the original brownfield soil;
- the minimum distance is exceedingly high – over 200 km – for raw material input and some energy-related impacts, especially for the SRC cropping system. This means that as long as the byproducts used in soil construction can be used to replace significant amounts of energy-intensive quicklime, LORVER's burden can only be alleviated if this valorization is done more than 200 km away from their source.

6. Conclusions

To our knowledge, this paper describes the first life cycle assessment of constructed Technosols for plant cultivation for industrial purposes, such as those developed in the context of the LORVER project. Here, the soil construction using inert and organic wastes made it possible to cultivate hemp and poplars for further use. The empirical evidence demonstrates the ability of constructed Technosols to provide ecosystem services such as: fiber or biomass-based energy source provisioning, global climate regulation (through organic and inorganic carbon storage), preservation of groundwater resources (through the stabilization of the remaining pollutants), offering a habitat for biodiversity, enhancement of the landscape amenities (through revegetation of the brownfield), and redevelopment of socioeconomic activities (through the activity of a farmer).

This paper proposed the first quantification of some of these services through the accounting of land clearing and artificialization; greenhouse gas, nutrient and pollutant emissions; and their comparison with plausible alternative scenarios. However, this quantification needs (1) to be refined and experimentally validated over the long term and (2) to be better integrated in the broader framework of the ecosystem services' assessment in an LCA.

Moreover, this paper has shown that the environmental impacts of such a Technosol should be assessed on a case-by-case basis. Indeed, these impacts depend greatly on the type of materials used for soil construction, which in turn depends on the desired soil agronomic properties, themselves depending on the desired crop. Furthermore, the material properties play a key role in the potential pollutant release and/or stabilization, fitness of cropping systems, and alternative valorization chains. Given the large amounts of materials at stake (approximately 10,000 $t \cdot ha^{-1}$), it is necessary to carefully consider how they would be managed, if not used for soil construction, and whether a more closed-loop recycling would be more relevant, from an environmental perspective. Thus, the present case study highlighted a trade-off between improved soil functionality and depleted air quality due to an indirect increase in energy-intensive inputs (lime).

Finally, considering Technosol eco-design applications, this paper emphasizes several recommendations: (1) carefully choose the used materials, minding whether alternative uses are more environmentally relevant, (2) use local materials and (3) optimize the amount of materials per surface area to cover, regarding the trade-off between regained soil functionality and the potential reclaimable surface area. The sensitivity analyses conducted in this paper, which support these recommendations, could be refined and integrated into a decision-making tool for Technosol eco-design.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.11.152.

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